# On the Galactic Center Being the Main Source of Galactic Cosmic Rays as Evidenced by Recent Cosmic Ray and Gamma Ray Observations

**Y.Q. Guo, Z.Y. Feng, Q. Yuan, C. Liu, H.B. Hu**

Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Science, Beijing 100049, P.R.China

E-mail: fengzy@ihep.ac.cn

**Abstract.** We revisit the idea that the Galactic center (GC) is the dominant source of Galactic cosmic rays (GCRs), based on a series of new observational evidence. A unified model is proposed to explain the new phenomena of GCRs and $\gamma$-rays simultaneously. The GCRs are thought to be accelerated during past activities of the GC. The pair production process of GCRs in the strong radiation field due to the GC activity is responsible for the knee structure of the cosmic ray spectra. A fraction of $e^+e^-$ produced by pair production interactions, can be reaccelerated in the induced bipolar jets and be transported into the halo, leaving the Fermi $\gamma$-ray bubbles and WMAP microwave haze as the remnant signal. Finally, the CRs diffuse in the bulge could further interact with the interstellar medium to produce low energy $e^+e^-$. After cooling down, these positrons may annihilate to produce the 511 keV line emission as discovered by INTEGRAL.

## 1. Introduction

The origin of cosmic rays (CRs) has been a mystery since their discovery in 1912. CRs have a nearly featureless power-law spectrum with a spectral index of about $-3$ from energies of $\sim 10^9$ to $\sim 10^{20}$ eV. However, detailed measurements revealed several subtle structures in the CR spectrum at $\sim 4 \times 10^{15}$ eV (knee), $\sim 4 \times 10^{17}$ eV (2nd knee), $\sim 5 \times 10^{18}$ eV (ankle), and $\sim 6 \times 10^{19}$ eV (Greisen-Zatsepin-Kuzmin cut-off) [1]. The study of these structures is of great importance for understanding the origin, propagation and interaction of CRs.

It is generally believed that supernova remnants (SNRs) are the sources of Galactic CRs (GCRs), based on the simple argument that the power by SNRs is sufficient to sustain the total power of GCRs [2, 3]. However, the $\gamma$-ray observations of SNRs tend not to favor the CR nuclei acceleration in SNRs [4]. There is also no direct evidence for CR nuclei sources among the thousands of GeV $\gamma$-ray sources [5] and more than one hundred TeV $\gamma$-ray sources‡. Other arguments against the SNR origin of GCRs can be found in e.g., [6, 7].

Instead of discussing the stellar level sources in the Galaxy, the Galactic center (GC) as powered by the accretion of the supermassive black hole, could be a natural candidate of CR origin. Although the GC is relatively quiet nowadays, there is large amount of evidence suggesting that the GC may have been active $\sim 10^7$ years ago [8, 9, 10]. Historically, here have been many discussions on the possibility that the GC is the dominant source of GCRs as a result of its activity [11, 12, 13].

There are great progresses in the measurements of GCRs and $\gamma$-rays in recent years. First, owing to the improved energy resolution, a very sharp knee structure was found by many air shower array experiments [14, 15, 16, 17, 18, 19]. This result seems to favor the single source model as proposed in [20, 21]. Second, several high precision measurements led to the discovery of both the positron fraction excess [22] and the total $e^+e^-$ spectral excess [23, 24] from $O(10)$ GeV to TeV. It was also shown that the $e^+e^-$ spectra have a cutoff at several TeV [25, 26]. The result seems also to favor the single source model proposed in [27]. Since the observational anisotropy of CRs is very weak ($10^{-4} \sim 10^{-3}$), the single source should not be very close to us. The GC is one of the potential candidates [28]. Furthermore, the discoveries of the 511 keV line emission and $\gamma$-ray bubbles in the GC region indicate that the GC may indeed have past activities. Based on these new observational data, it is time to revisit the idea that the GC is the main source of GCRs.

In this work we describe a unified model to explain the recent observations of CRs and $\gamma$-rays, based on the past activity of the GC.

‡ http://www.mpp.mpg.de/∼rwagner/sources/

## 2. Model

During the active phase of the GC, the accretion of stars and gases by the supermassive black hole is very efficient to provide high enough power for particle acceleration, jet launch and propagation. The GC activities can produce shocks and accelerate CRs to high energies [29, 30] in scales from $\sim 10^{-3}$ pc [31] to kpc [32]. The heating of the accretion disk makes it filled with thermal photons. Jets could also be produced due to the accretion events.

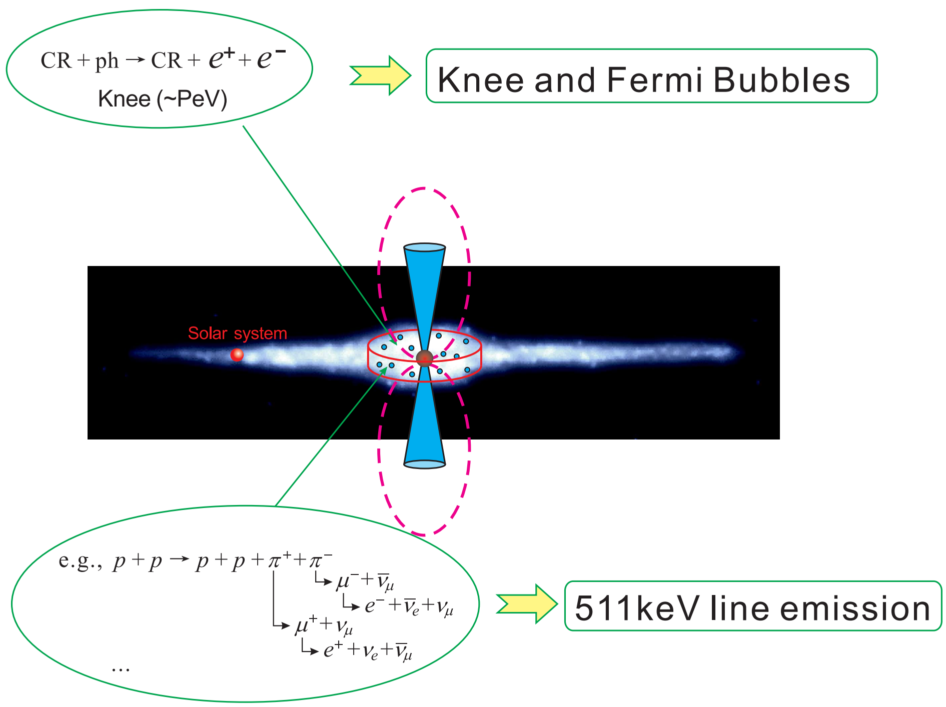


**Figure 1.** Cartoon of the model.

In the above mentioned environment, the following physical processes are expected to occur. First we may have the primary acceleration of CRs around the black hole. The accelerated nuclei can then escape from the source region and enter the disk filled with background field. The interaction between CR nuclei and the background photons can lead to energy loss of CRs, which could result in the formation of the knee [27]. The interaction will produce $e^+e^-$ pairs, which can be partially transported into the halo through the jets. Those electrons and positrons can then radiate to form the multi-wavelength haze/bubble. Finally the CRs diffuse in the bulge could further interact with the interstellar medium to produce low energy $e^+e^-$. After cooling down, these positrons may annihilate to produce the 511 keV line emission. The cartoon to describe the basic picture of the model is shown in Fig.1. In the following we will discuss more details about the three aspects, the origin of the knee, the multi-wavelength haze/bubble and the 511 keV emission respectively.

*2.1. Origin of the Knee*

Ref. [27] proposed a model to simultaneously explain the knee and the $e^+e^-$ excess, incorporating pair production interactions between CRs and the ambient photon field. It was further shown that the irregular structures of the CR spectra around the knee region and the Galactic "B component" could also be well explained in this scenario [34]. As a consequence, one set of parameters in the mode of [27] also favors the single source model. It indicates that there might be a single source with relatively stable properties (during the CR acceleration period) that is responsible for GCRs.

In [27], a supernova-pulsar system was proposed as a possible candidate for such a source. Though it is not impossible, it seems non-trivial for such a system to satisfy the conditions needed to produce the knee of the CRs [35]. Alternative candidate sources may include micro-quasars or the Galactic center (GC). The latter seems to be an especially attractive option [28]. As proposed by many studies, the capture of stars or accretion of gas by the central supermassive black hole can produce shock and accelerate particles [29].

The density of background radiation field at GC region is the key point whether the knee structure of CR spectra can be formed. As shown in [27], the photon column density should be $\sim 10^{30}$ cm$^{-2}$. Without firm observational evidence of the size of such kind of interactions, we take 1 pc as an illustration. The optical photon density inside 1 pc of the GC is about $5 \times 10^4$ eV/cm$^3$ in a flare disk and dust [36]. The diffusion velocity of CRs in the knee region is estimated to be the order of $10^{-3}$ of the light velocity, according to the measured anisotropy [37]. Therefore, the time for CRs to diffuse out of such a region is about $10^3$ yr. So the photon column density which CRs can encounter is $nc\tau \sim 10^{26}$ cm$^{-2}$, which is 4 orders of magnitude lower than that required. However, it is possible that the photon luminosity could be much higher during the active phase than at present. For example, the observation of infrared radiation from other galaxies showed that when the nucleus was in the active phase the infrared luminosity could be as high as $10^{44} - 10^{47}$ erg/s, which is $2-5$ orders of magnitude higher than the present value of our Galaxy, $\sim 10^{42}$ erg/s [11]. Therefore it is possible that the background photon density could be 4 orders of magnitude higher during the active phase, and the condition to form the knee could be satisfied. Under these circumstances, the total energy of background photon is estimated to be $\sim 10^{53}$ erg, which is close to the accretion power of one solar mass.

*2.2. Fermi bubbles: possible relics of past GC activity*

If GC indeed plays a significant role to produce the Galactic CRs, we may expect the existence of some relics of the past activity of GC. "Fermi bubbles", the new observational evidence, may be such kind of relics of the past GC activity.

Thanks to the high performance of Fermi $\gamma$-ray telescope, a large scale, extended $\gamma$-ray excess in the GC direction was discovered [38], which was then revealed to be two giant $\gamma$-ray bubbles [39]. The Fermi bubbles are symmetric with respect to the

Galactic plane, extending $\sim$ 50 degrees in latitude and $\sim$ 40 degrees in longitude. They are spatially correlated with the WMAP haze observed in the $20 - 60$ GHz band [40, 41], and the edges of the bubbles are also found to be coincident with features in the ROSAT $1.5 - 2$ keV X-ray maps [42]. Recently, the PLANCK collaboration confirmed the microwave haze found in WMAP data [43]. Several models are proposed to explain the Fermi bubbles [33, 44, 45, 46, 47, 48, 49], most of which are based on the GC activity in the past.

The bubbles are found to have a hard $\gamma$-ray spectrum between 1 and 100 GeV, with a power law index $\sim -2$. The $\gamma$-ray spectrum can be well reproduced by the inverse Compton scattering (ICS) process of power-law distributed electrons with index $-2 \sim -2.5$ [39], taking into account the cosmic microwave background, infrared and optical background radiation. In addition, the calculated synchrotron radiation can reproduce the radio haze flux, assuming that the magnetic field is of the order of 10 $\mu$G. However, this electron spectrum has difficulty to explain the observed low energy drop below 1 GeV. In order to solve this problem, an electron population with limited energy range was proposed. Based on these facts, Su et al. [39] concluded that the bubbles are most likely created by a large episode of energy injection in the GC in the last $10^7$ years through an accretion event in the center of supermassive black hole, a nuclear starburst or some other energetic event.

The locally measured energy density of CRs is about 1 eV cm$^{-3}$. Giving that the volume of the Galactic disk is about $\pi(20\,\mathrm{kpc})^2(0.2\,\mathrm{kpc}) \sim 10^{67}$ cm$^3$, the total energy of CRs is about $10^{55}$ erg. Assuming the pre-propagated spectrum of GCRs is $\propto E^{-2.0}$, the total energy of GCRs above the knee ($E \sim$PeV) is approximately $10^{54}$ erg. Such an energy will be mostly converted into $e^+e^-$ through the pair production interactions. According to [39], the Fermi has an age on the order of $10^7$ yr. It is to say that the luminosity of $e^+e^-$ is estimated to be $10^{39} - 10^{40}$ erg/s . The total luminosity of the Fermi bubbles in $1 - 100$ GeV is estimated to be about $4 \times 10^{37}$ erg/s [39], which is much smaller than the above estimated value. That is to say, the produced $e^+e^-$ could be possible to generate the Fermi bubbles.

It should be noted that in the strong background radiation field, electrons/positrons may cool down very efficiently. However, it is expected that there should also be acceleration in the jets, which may more or less compensate the cooling of the electrons/positrons. The $e^+e^-$ spectrum used to calculate the synchrotron and ICS spectra is adopted from [27], which can explain the $e^+e^-$ excesses observed by PAMELA/ATIC/Fermi. For the interstellar radiation field (ISRF) model we adopt that reported in Porter & Strong [50], in which a new calculation based on the modelings of star and dust distributions, the scattering, absorption and re-emission of the stellar light by dust, was carried out. The ISRF model showed good agreement with the observational data [51], and was implemented in the public CR propagation code GALPROP [52]. Here we adopt the ISRF intensity at $R = 0$ and $z = 4$ kpc. The energy spectrum of the ISRF is shown in the left panel of Fig. 2. Three major components, optical from stars, far-infrared from dust and the cosmic microwave background (CMB),

are clearly shown.

The right panel of Fig. 2 shows the resulting synchrotron and ICS spectra by the $e^+e^-$. The magnetic field is assumed to be $B = 15\mu$G, and the Klein-Nishina cross section of ICS is adopted. The spectra of WMAP synchrotron haze and Fermi ICS bubbles are consistently generated.

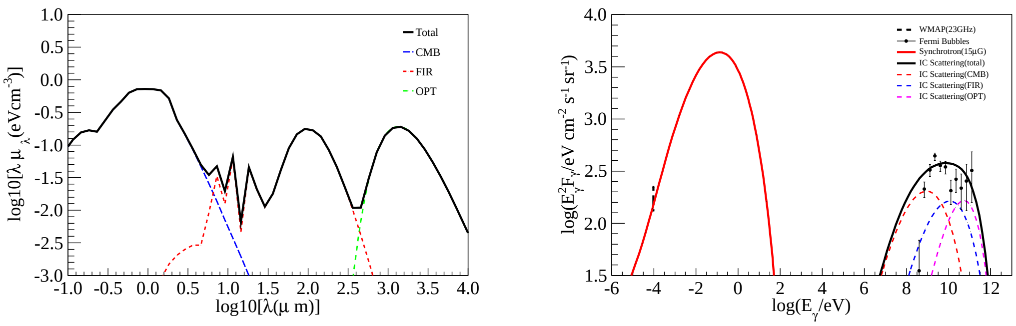


**Figure 2.** Left: the ISRF at $(R, z) = (0\,\text{kpc}, 4\,\text{kpc})$, adopted from GALPROP package. Right: The calculated spectrum of ICS $\gamma$-rays and synchrotron radiation originating from a re-accelerated electron spectrum generated through CR-photon pair production interactions. The line of sight direction is chosen to be $l = 0°$ and $b = 25°$. The data points representing the Fermi bubbles and WMAP haze are taken from Table 3 and Fig. 23 of [39].

### *2.3. 511 keV line emission*

It is natural to expect a possible connection of the GC origin of CRs with the 511 keV line emission as reported by several experiments [53, 54, 55, 56], although the most popular model of 511 keV emission is the decay of radioactive isotope[57]. The 511 keV line emission indicates the existence of non-relativistic positrons in the GC region. The hadronic interactions of GCRs with the ambient gas could be one potential source of these positrons [29, 58, 59]. We make an order of magnitude estimate of the power of electrons. The total number of CR protons is about $\sim 10^{58}$, for a local number density of $\sim 10^{-9}$ cm $^{-3}$ and the volume of the Galactic disk $\sim 10^{67}$ cm$^3$. Considering that the size of the Galactic bulge is $\sim 1$ kpc, the typical path length that a particle travels from the GC to outside of the bulge should be $\sim 10^3$ kpc, for diffusion coefficient $D \sim 5 \times 10^{28}$ cm$^2$ s$^{-1}$. Assuming that the number density of ISM nuclei in the bulge is 1 cm$^{-3}$, and the inelastic cross section of $p - p$ scattering is several tens of mb, the average number of collisions for one CR proton before traveling out of the bulge is $\sim 0.1$. Thus, the total number of positrons is $\sim 10^{57}$. Assuming the cooling time of positrons is about $10^7$ years, which corresponds to the ionization and Coulomb losses in an ISM with density of 1 cm$^{-3}$ for a 100 MeV positron [52], the cooled positron production rate is $3 \times 10^{42}$ s$^{-1}$, which is comparable with the rate $10^{43}$ s$^{-1}$ as implied from the flux of 511 keV $\gamma$-ray line [54].

However, it was pointed out that the diffuse $\gamma$-ray constrained positron production

rate would be not more than a few percent of the positron rate suggested by the 511 keV emission data [29, 54, 60]. This problem can be solved in a non-stationary scenario that the GC was in active phases in the past and the positron production rate would be much higher than that determined by the current diffuse $\gamma$-ray flux [29, 60].

## 3. Conclusion and discussion

In this work we proposes that the GC is the major source of GCRs. There is evidence to show the past activity of the GC. Particle acceleration can take place during the violent phase of the GC. Also it is expected the existence of strong radiation field around the GC. Thus an efficient $e^+e^-$ pair production interactions between GCRs and the ambient photons might be responsible for the the knee of the CR spectra [27]. A fraction of $e^+e^-$ produced by pair production interactions, can be reaccelerated in the jets and escape into the halo. The ICS and synchrotron radiation of these $e^+e^-$ may possibly explain the observed Fermi bubbles and WMAP haze.

Even the jet can transport the $e^+e^-$ very efficiently into the halo, the propagation of these particles from the jet to the whole bubble is still a question. Because of the lack of knowledge about the Galaxy magnetic field, phenomenological model is generally used to study the propagation of GCRs in the Galaxy. As we know the halo is much larger than the disk. But the average density of the medium GCRs travel is $\sim 0.3$ cm$^{-3}$ while the disk density is about 1 cm$^{-3}$ [61]. So the trapping time of GCRs in the halo is only about two times longer than in in the disk. We can infer that the propagation velocity in the halo is much faster than in the disk. It is possible to conclude that the stochastic magnetic field is much smaller in the halo than in the disk. We need to investigate the particle transportation in the regular halo magnetic field [62] to study propagation of particles in the halo, instead of the uniform diffusion in the Galaxy. Therefore the $e^+e^-$ may fill in the whole bubble within the cooling time through the fast propagation. However, the detailed model goes beyond the scope of the current work.

The anisotropy of GCRs may still an open question in the GC scenario of the origin of GCRs. Still the different propagation parterns in the disk and the halo may lead to different results of the expected anisotropy. We leave the discussion of it in future works.

Finally we should note that in the jet the background electrons should also be accelerated together with the $e^+e^-$ produced through CR-photon interactions. In such a case the total electron spectrum used to calculate the bubble/haze emission might be different from what adopted in this work. Without loss of generality, we may expect the background electron spectrum to be a power-law spectrum $\sim E^{-2}$ with a cutoff, which does not differ much from that we use here. The basic results in this work should not change significantly.

## Acknowledgements

We thank Shaoxia Chen for helpful discussion, Yigang Xie, Amanda Maxham, Ann Meng Zhou and Hanguo Wang for useful comments on the manuscript. This work is supported by the Ministry of Science and Technology of China, Natural Sciences Foundation of China (Nos. 10725524,10773011 and 11135010), and the Chinese Academy of Sciences (Nos. KJCX2-YW-N13, KJCX3-SYW-N2, GJHZ1004).


## References


[1] Hörandel, J. R. 2007, Modern Physics Letters A, 22, 1533
[2] Baade, W. & Zwicky, F. 1934, Phys. Rev., 45, 138
[3] Ginzburg, V. L. & Syrovatskii, S. I. 1964, The Origin of Cosmic Rays (New York:Macmillan)
[4] Abdo, A. A., et al. 2011, ApJ, 734, 28
[5] Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJ, 199, 31
[6] Hillas, A. M. 2005, Journal of Physics G Nuclear Physics, 31, 95
[7] Butt, Y. 2009, Nature, 460, 701
[8] van der Kruit, P. C. 1971, A&A, 13, 405
[9] Sanders, R. H., & Prendergast, K. H. 1974, ApJ, 188, 489
[10] Erlykin, A. D., & Wolfendale, A. W. 2007, Journal of Physics G Nuclear Physics, 34, 1813
[11] Ptuskin, V. S., & Khazan, Y. M. 1981, AZh, 58, 959
[12] Said, S. S., Wolfendale, A. W., Giler, M., & Wdowczyk, J. 1981, ICRC, 2, 344
[13] Giler, M. 1983, Journal of Physics G Nuclear Physics, 9, 1139
[14] Chilingarian, A., et al. 2007, Astroparticle Physics, 28, 58
[15] Korosteleva, E. E., Prosin, V. V., Kuzmichev, L. A., & Navarra, G. 2007, Nuclear Physics B Proceedings Supplements, 165, 74
[16] Garyaka, A. P., et al. 2008, Journal of Physics G Nuclear Physics, 35, 115201
[17] Amenomori, M., et al. 2008, ApJ, 678, 1165
[18] Apel, W. D., et al. 2009, Astroparticle Physics, 31, 86
[19] Ivanov, A. A., Knurenko, S. P., & Sleptsov, I. Y. 2009, New Journal of Physics, 11, 065008
[20] Erlykin, A. D., & Wolfendale, A. W. 1997, Journal of Physics G Nuclear Physics, 23, 979
[21] Erlykin, A. D., & Wolfendale, A. W. 2009, arXiv:0906.3949
[22] Adriani, O., et al. 2009, Nature, 458, 607
[23] Chang, J., et al. 2008, Nature, 456, 362
[24] Abdo, A. A., et al. 2009, Physical Review Letters, 102, 181101
[25] Aharonian, F., et al. 2008, Physical Review Letters, 101, 261104
[26] Aharonian, F., et al. 2009, A&A, 508, 561
[27] Hu, H.-B., et al. 2009, ApJ, 700, L170
[28] Hu, H., Rapporteur paper, Proceedings of the $31^{st}$ ICRC, Łódź 2009, arXiv:0911.3034
[29] Cheng, K. S., et al. 2006, ApJ, 645, 1138
[30] Bell, A.R., Lucek, S.G., 2001, MNRAS, 314, 65
[31] Albert, J., Aliu, E.,Anderhub, H., et al. 2008, ApJL, 685, L23
[32] Su, M., et al., 2012, ApJ, 753,61
[33] Guo, F. et al. 2012, ApJ, 756, 182
[34] Wang, B., et al. 2010, Science in China G: Physics and Astronomy, 53, 842
[35] Erlykin, A. D., Wibig, T. & Wolfendale, A. W. 2011, Astrophysics and Space Sciences Transactions, 7, 179
[36] Davidson, J. A., et al. 1992, ApJ, 387, 189
[37] Aglietta, M., et al., 2003, ICRC, 183
[38] Dobler, G., Finkbeiner, D. P., Cholis, I., Slatyer, T., & Weiner, N. 2010, ApJ, 717, 825

[39] Dobler, G., Finkbeiner, D. P., Cholis, I., Slatyer, T., & Weiner, N. 2010, ApJ, 717, 825
[40] Finkbeiner, D. P. 2004, ApJ, 614, 186
[41] Dobler, G., & Finkbeiner, D. P. 2008, ApJ, 680, 1222
[42] Snowden, S. L., et al. 1997, ApJ, 485, 125
[43] Ade, P.A.R., 2012, arXiv:1208.5483v1
[44] Cheng, K. S., et al. 2011, ApJ, 731, L17
[45] Crocker, R. M., & Aharonian, F. 2011, Physical Review Letters, 106, 101102
[46] Guo, F., & Mathews, W. G. 2011, arXiv:1103.0055
[47] Istomin, Y. N. 2011, arXiv:1110.5436
[48] Mertsch, P., & Sarkar, S. 2011, Physical Review Letters, 107, 091101
[49] Zubovas, K., King, A. R. & Nayakshin, S. 2011, MNRAS, 415, 21
[50] Porter, T. A., & Strong, A. W. 2005, ICRC, 4, 77
[51] Moskalenko, I. V., Porter, T. A., & Strong, A. W. 2006, ApJ, 640, L155
[52] Strong, A. W., & Moskalenko, I. V. 1998, ApJ, 509, 212
[53] Johnson, W. N., et al. 1972, ApJ, 172, L1
[54] Knödlseder, J., et al. 2005, A&A, 441, 513
[55] Jean, P., et al. 2005, A& A, 445, 579
[56] Weidenspointner, G., et al. 2008, Nature, 451, 159
[57] Prantzos, N. et al, 2011, RvMP, 83, 1001
[58] Ramaty, R. et al. 1970, Journal of Geophysical Research, 75, 1141
[59] Totani, T. 2006, PASJ, 58, 965
[60] Porter, T. et al. 2008, ApJ, 682, 400
[61] Maurin, D., et al., 2001, ApJ, 555, 585
[62] Beck, R. 2001, Space Science Reviews, 99, 243